From: "Hasan Gazi ICOZ" <yxkhasan81@hotmail.com>
To: wtc@nist.gov
Subject: Comments on NIST Draft Report NCSTAR1-1. The WTC......London

Dear Mr. Stephen Cauffman

National Institute of Standarsd and Technology
WTC Technical Information Repository
Stop 8610
Gaithersbutg, MD 20899-8610 USA

Attachhed pleasse find our Comments on WTC Disaster Scanario in relation to the above report. In principle we are in aggrement with NIST on certain major findings. There are a number of research cases where NIST have not spelt out in detail or missed out. Our contributions shall be considered as addudum to the above excellent report. We would appreciate if they may please be edited on the lines required by your final report. If you require our assistance at editing stage please do not hesitate to conctact the undersigned.

Prof. Dr. M.Y.H Bangash

Note: A CD containing all that has been given to you by e-mail is being sent to you with our compliments.

nist.doc

NIST NCSTAR 1 (Draft)

Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Final Report of the National Construction Safety Team on the Collapse of the World Trade Center Towers (Draft)

For Public Comment

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BSc, BE, MSc, Ph.D, DSc(Eng), C Eng, FICE, FIStrutE, FASCE, MACI, FIE, C Eng, Fi Nucl E, MPCI, MBNES, MAIAA

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NIST

National Institute of Standards and Technology. Technology Adminitration – U.S. Department of Commerce

Introduction

Numerous case studies can be considered. A Literature Survey indicates that several structures had been subject to impact / explosion and fire. Various techniques of analyzing such structures have been fully described and as far as possible, several numerical models and analytical approaches are given to examine individual isolated cases and global structures which maybe subjected to aircraft / missile crashes, explosion aid fire. The reader has been given choices to intimate cases, which need urgent considerations. At the time of writing of this comment, several more disaster scenarios might have occurred and which couldn't be recorded. It is intended to present some well-known case studies, which might have bearing on identical disaster scenarios.

The following well-known cases are identified:

- WTC Towers in New York, U.S.A.
- The Oklahoma City Building, Alfred hurrah Building, Oklahoma U.S.A.
- The Pentagon Building in Washington D.C., U.S.A.
- The HSBC Building in Istanbul, Turkey

It should be not noted that the current submission concerns the WTC Towers in New York:

The federal investigation into the collapse of the World Trade Centre towers on Sept. 11, 2001 has been unable to pinpoint what engineering elements were critical in the disintegration of the buildings or how best to resist a recurrence. Eve so, the six-month study - conducted by the American Society of Civil engineers and the Federal Emergency Management Agency (FEMA) has revealed some disturbing facts abort modem skyscrapers that are potentially worrisome for those who work or live in high-rise buildings around the country.

The most encouraging finding was that the impact forces of the huge jets that rammed into the towers were not the only ones, by themselves, to cause the collapse. Although the twin towers were designed to handle only the crash of a Boeing 707 flying at low approach speeds, the FEMA report indicates when put to the test on Sept. 11 they absorbed the shock of slightly heavier Boeing 767's flying at much higher speeds. Had no other stresses caused by explosion and fire been imposed on the structures, they could have remained standing indefinitely.

Unfortunately there was added stress effects, in the form of extremely hot fires that resulted when jet fuel ignited the contents of the buildings and planes. The flames softened the structural steel, triggering events that allowed the upper floors to cascade downward.

All three major defences against fire proved unequal to the task. The sprinkler systems were disabled by the impact of the planes. Firemen were unable to reach the inferno because emergency elevator's were damaged, and even if they had arrived in force, the sandpiper they needed were almost certainly disabled. Finally, the fireproofing material sprayed on steel beams and trusses to protect against overheating failed to do so, notably because most of it was blasted off by the planes' impact. Whether better insulation is needed, at least for the most critical structural elements, 11 be one focus of additional inquiry.

The experts appointed were unable to determine whether the fires alone, without the impact of the airplanes, could have brought the towers down. But it is to learn that an adjacent history building collapsed completely as a result of a fierce fire fed by diesel oil on the premises, and that another building suffered a partial collapse from fire. These are the first known instances pf protected steel-frame structures collapsing from severe fire, suggesting that many modern building may be more vulnerable than anyone realized.

The investigation has put a spotlight on longstanding practices that will surely need revision in the wake of his disaster. It seems absurd that steel beams are tested for fire resistance, whereas the steel connection that hold them together are generally not. Nor is analysis made of how an integrated structure, not just its individual components, will respond to fires, or impact how fires and structural damage interact.

A more through three-year invesitigation has been conducted by the Natinal Institute of Standars and Technology (NIST) and published a final draft NIST NGSTAR 1 for public comment in 2005 on the safety investigation of the World Trade Centre Disaster. The report contains excellent factual data and recommendations with some creative interpretation. Some of these require serious considerations with final comments from the contributors.

CS.2 A Background to Comments on the Report.

Since 9/11, 2001, the co-author Dr. T. Bangash and myself have been working on the WTC Twin Towers and their collapse scenarios. We were familiar with the design of towers by Mr.Yamasaky, the architect in 1961. When the FEMA Report was published on Twin Tower Collapse scenarios in May 2002, we did approach, the famous technical publishers SPRINGER-VERLAG of Heidedberg, Germany, our intentions of publishing our finding on Twin Towers. As a result, after working on the analytical, numerical, design evaluations and preparation of advance softwares for the pre and post processing of results, we have managed to produce the fallowing book on:

EXPLOSION RESISTANT BUILDINGS
Design, Analysis and Case Studies, Aug 2005

The flyer given as PLATE No.1 shows the major contents of the book and it is intended to be considered as part of our public comment as asked for by NIST.

The entire work hinges on two vital methods of analysis:

- Three-dimensional Hybrid Dynamic Finite Element Technique involving subroutines such: BANG FIRE, BANG – BLAST, BANG-IMP ETC; Flow charts given on PLATE No.2 will explain the mechanism of the MASTER BANG-F.

- Three dimensional Finite/Discrete Element Method of Analysis developed by Dr. T. Bangash for his Ph. D programme of the London University 2004. This is a much more simplified method incorporating all effects of blast, fire and impact as stated under 3D Hybrid Finite Element Technique. This method reduces CPU Time by 50% and has been fully tested with Finite Element and applied successfully to Alfred Murrah Building at Oklahoma, USA

Three modified and adjusted versions of the fallowing softwares were considered for individual case studies such as aircraft impact on containment vessels for PWR, Fire-cum-Thermal Effects on global buildings and building internals of a high rise building in U.K. and Blast Loading Effects on concrete and steel structures.

PLATE 1

M.Y.H. Bangash; T. Bangash

Explosion-Resistant Buildings

Design, Analysis, and Case Studies

2005. Approx. 450 p.
Hardcover. EUR 149.95; £ 115.50; sFr 254.-
ISBN 3-540-20618-3

This excellent book highlights all aspects of the analysis and design of buildings subject to impact, explosion and fire. It is a definitive reference book and contains 10 sections from a wide international prospective. Three-dimensional finite element and discrete element techniques are included. They are applied to buildings such as the World Trade Center (WTC Twin Towers) and the Federal Building in Oklahoma on the basis of the designers drawings, data and other information. Many small case studies are also included. The book has a comprehensive bibliography and a large appendix providing background analysis and computer subroutines of recently developed programs.

From the contents:
Explosion and Buildings.- A Review of Affected Buildings and General Criteria, Data and Management.- Blast and Explosive Loadings on Buildings.- Fire and Buildings With and Without Explosion/Impact.- Structural Response to Blast Loadings - Methods of Analysis.- Blast Response Resistance - Design of Structural Elements.- Contact or Gap Elements for Blast-Fire Structural Interaction.- Aircraft and Missile Impact - Data and Analysis.- Aircraft Hot Fuel-Structure Interaction during Impact Condition.- Flying Debris - Elastic Scattering Approach.- Building Global Analysis for Damage Scenario.

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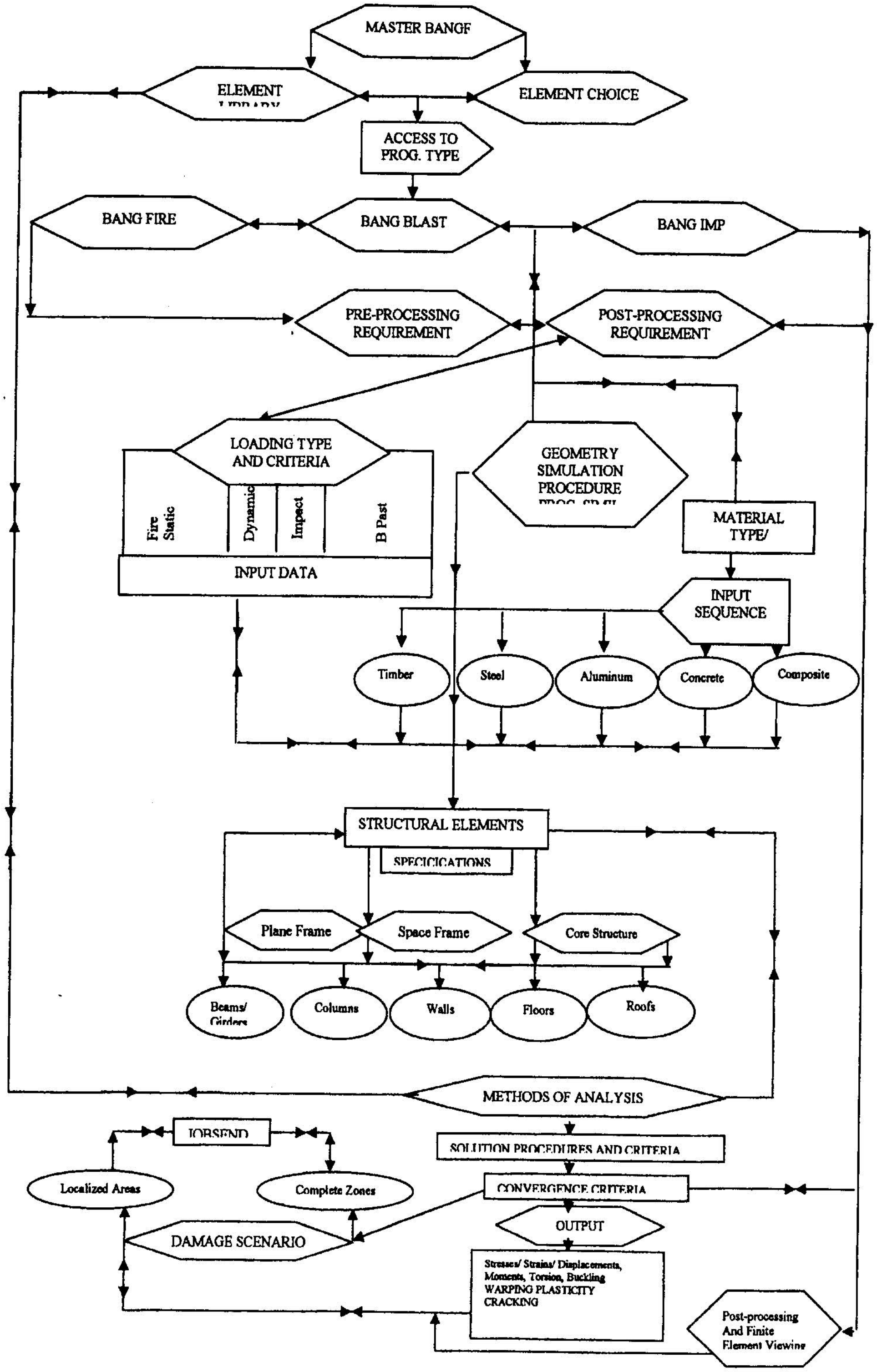
PLATE 2

FLOW CHART FOR PROGRAM BANGF (GLOBAL FINITE ELEMENT ANALYSIS)



(a) Program ISOPAR
(b) Program ANSYS
(c) Program LS DYNA
(d) Program Finit/Discrete

With FEMVIEW: For Viewing and PATRAN

Prior to the applications of these programs to WTC 1 and WTC 2, the analytical methods and software have been tested against known case studies fully collaborated with experimental results and wherever possible site monitoring.
In order to produce a disaster scenarios, the Master Program Bang-F asks for requisite any subroutines examined by the SUB PROGRAM EVOL, prior to passing on to program.

FEMVIEW or F.PATRON which maintain the numerous recorded pictures of the "Disaster Scenario" The function of the subprogram EVOL is also to check out whether or not BANG-F would scenario matches with the already stored scenario. If they are the same BANG-F would release all the numerical results and graphical disaster scenarios. Assuming they do not agree, they then go back as stated in the PLATE No. 2 to rediscover changed parameter and start all over again till the desired objective has been achieved. When the results are finally obtained, they either tabulated and or finally plotted. The same procedure is valid under debris impact, fire affected Components and Explosion on Structures or Structural elements.

This concept is the basis of the evolution of disaster scenarios of the WTC Twin Towers 1 and 2. It should be noted that the WTC Towers 1 and 2 have fallowed the NYC codes of building design:

- Each tower was designed to support dead loads (its own weight) consistent with the provisions in the 1968 NYC Building Code. The dead loads included the weight of the structural system and loads associated with architectural, mechanical, plumbing and electrical systems.
- Each tower was designed to support live loads (the combined weights of the people and the building contents) exceeding those specified in the 1968 NYC Building Code.
- The design wind loads used in the towers were higher than those required by the 1968 NYC Building Code and three other codes identified earlier.
- Each tower has not been tested as a sensitized design against withstanding the impact of a fuel-laden commercial jetliner, although the impact analysis had been carried out at design initial stages analysis with the impact of Boeing 707 aircraft flying at 600 mph against twin towers.

CS. 3 Problems Associated with the collapse of the towers – Initial Assessment

Various result are highlighted. Some these are briefly given below part of the overall discussions.

(a) When the. buildings WTC came down, as gravitational potential energy unloaded, and its value computed is around 6.8 x 10"7J. (Compared to this, the energy of a severe earthquake would be10^{17} J and thermal energy output of a reasonably large power station would be 10^{16} J). As a matter of fact, the collapse created an earthquake of 10 magnitude 2.4 on the Richter scale. However, unlike a normal earthquake, they were richer in low frequency energy and poorer in high frequency energy, the main reason for this being the gravitational potential energy due to the falling of building material. According to Prof. Mackin, of the University of Illinois at Urbana-Champaign, an aircraft has the equivalent power of a small-scale commercial power plant. The kinetic energy of a 767jet at impact is of the order of 40 mega joules as shown below:

$$KE = \frac{1}{2}mv^2$$

where m = mass = 204×10^3 kg

v = velocity = 19.7 m/s

KE = kinetic energy = $39.6 \times 10^6 = 40$ MJ

Though this energy is considerable, it is clear that the towers withstood this impact. Though damaged, two WTC managed to remain standing for approximately one hour, and one WTC for 90 minutes. The elemental analyses show that it was not to impact, but the energy in the fuel that affected the structural integrity of the building. The energy content of fuel is approximately 35×10^6 joules per litre. (Jet fuel may have even greater energy content). Assuming that the jet had 75,700 litres of fuel, (fuel capacity of 767 jet is 90,764 litres) and it detonated at once, the resulting energy would be 792×10^9 joules. This would amount to the equivalent of 2, 376, 000 sticks of dynamite (3 sticks of dynamite will have 1 mega joule of energy).

If one assumes that the jet liner with a weight of 205 tonne was traveling at cruising speed (850 km/hr) and dissipated all of its energy in one second, their torque on building shall be = F x moment arm = 857×10^3 KNm, where F = MV = momentum per second = 4018 KN. If the plane hits the 70^{th} floor, the torque at the base will be 857×10^3 KNm. Later on the global torque analysis given in the text could envisage the W.C. tower with standing this high impact. However, elemental analysis indicated that the impact of the plane crash destroyed a significant number of perimeter columns on several floors of the building, severely weakening the entire system. As the fire analysis indicates, as the fire raged in the upper floor, the heat gradually affected the remaining tower structure. The preliminary elemental analysis gives a firm belief that the steel core struts became weakened due to prolonged high temperatures fuelled by the large volumes of aviation fuel. The floor results showed from the elemental ad finite element program's due to the vertically directed 815 ^{o}C (1500 F°), the weakened struts collapsed collapsed mechanisms. This is the scientific explanation put forward for the catastrophic failure of the tower having intended to withstand an impact of aircraft such as that of a Boeing 767 jet aircraft.

The thermal environment within each tower is still a subject of discussion. Prior to the global analytical work on failure and collapsed scenario, it is essential the elemental analysis provided for components should be discussed in the light of Program BANG- FIR.

Based on preliminary assumptions and analysis, mathematical and numerical models have been used to estimate the behaviour of the fires in the twin towers of the World Trade canoe. The hijacked-plane collision with each tower produced significant structural damage, generated a spectacular external fireball, and started burning within the tower. The fuel consumed by the fireball was absorbed as an ignition source, but produced a pressure pulse that damaged windows and changed the ventilation for the fires. The subsequent are in each tower generated a quasi-static, wind-blown smoke plume. The fire and smoke behaviour were simulated using the program BANG-FIR (FDS). Comparison of the observed plume trajectory with the simulated one causes to estimate the rate of energy supplied by the fire to the plume which was of the order of magnitude of a gigawatt (GW). The rate of energy supplied to the plume, plus the energy-loss rate, determine the total heat release rate (I4RR), the most important single parameter for each tower fire. Two bounding scenarios for the interior damage and fuel distributions were considered by program BANG-FIR for the north tower. For each scenario, the simulated visible fire and smoke behavior outside the tower were compared with known photographing to determine which scenario seemed more appropriate. The simulations for the two scenarios also provided estimates of the likely thermal environment within each tower.

Because both towers were so completely destroyed when they collapsed, relatively little physical evidence remained for investigation. As a result, photographs have become the primary resource for providing initial estimates of the exterior damage to each building and of progression of the tire. These proved to be only source for comparing watts numerical models. Wind, pressure and temperature as functions of height, obtained from the records of the Aircraft Communications Addressing and Reporting System (AGARS), were also found to be critical input for the study. The finite element analysis provides program BANG-BLAST and program BANG-FIR have been examined.

CS4. Smoke Flame and Heat Analyses and Debris Release for Global Structures

The trajectory of the smoke plume convective energy convective energy parameters known to was used, in principle, to estimate the magnitude of per time contributed to the smoke plume by the tower fires. This rate, the wind speed and direction, and atmospheric stability are the govern a smoke-plume trajectory.

From photographs it was determined that the wind direction was almost exactly from the geographic north. We also established that the velocity of this wind was between 5 is and 10 is. The wind speed and direction were verified by data from the Aircraft Communications Addressing and Reporting System (ACARS), which also provided data on temperature and pressure as functions of height. From these data, assuming a perfect gas, one can also calculate air density as a unction of height, and these thermodynamic quantities determine the stability of the atmosphere. Commercial flights generally use ACARS to capture and retort temperature, pressure and wind speed and direction data as unction of altitude. It shows these quantities on the morning of 9/11 as obtained from three flights, one from JFK airport in New York and the other two from Newark International in New Jersey. Hence the analysis has used 5 is as the wind velocity and a lapse rate approximately one half the adiabatic lapse rate, which was -1.0 °C per 100 m.

As explained earlier, a full fuel load for each plane would be approximately 90,800 L or 74,500 kg of jet fuel, as noted earlier, the planes carried only approximately 31,000 to 34,000 L or 26,000 to 28,000 kg of jet fuel (density ρ_{fuel} = 0.82 kg/l. The area of one floor of either tower was 4025 m^2.

By contrast a second sophisticated analysis was uses a strictly Eulerian, mixture-fraction formulation to describe the combustion. In this model, the flame sheet was found where stoichiometry occurs, and the heat from the exothermic reaction is released into the flow along the flame sheet using BANG-FIR. The radiative transport is also handled in a more sophisticated fashion. An approximate solution to the full radiation transport equation, that accounts for local absorption and re-radiation by the material in the computational domain, is used to calculate radiative fluxes and, therefore, heat transfer by radiation. This formulation allows the radiation coupling that generates new gaseous fuel at solid surfaces. This method is applied for floors.

Detailed descriptions of the mathematical models used in both versions, and of the methods used to validate them are presented. The quality and ease of use of this tool have significantly improved the ability to understand fire behavior.

In the global analysis, the heat released per unit are in PROGRAM BANG-FIR is 2 MW/m^2. It assumed that plane dumped its whole fuel load over only one to two floors, smashing all material on those floors to an averaged depth of around 0.8 cm with fuel load of 6.2 kg/m^2 as part of the input to BANG-FIR. At the burning rate with heat release rate of 2 MW/m^2 the scenario established is the final attempt with time 10 minutes to spread over greater area. The estimate is consistent with that given in FEMA study Report. Throughout it is assumed in BANG-FIR that the jet fuel would be consulted quickly relative to the duration of the tower fire.

CS 5. PLUME-TRAJECTORY SCALING

The mass, momentum and energy equations stated earlier can be simplified by assuming a steady, non-zero horizontal wind blowing over a fire of heat release rate Q, assumed to be constant. Q is the most important parameter characterizing an outdoor fire.

Ambient stratification of the atmosphere, which is related to the meteorological concept of potential temperature, is included in this model. The atmospheric stability at any height is determined by the local density (or temperature) gradient and is specified by the local buoyancy frequency N = $\sqrt{(g/\rho(z))(d\rho(9z)/dz)}$. This frequency arises because the atmosphere is naturally stratified as a function of height, with the highest density air at ground level and smaller densities with increased height. The horizontal velocity is assumed to be uniform with height over the height of interest, although the more general theory allows for a velocity profile changing with height. Analytical scaling of the governing equations introduced in these papers yields the following important length scale:

$$L = \left(\frac{Q_g}{C_p T_a \rho_a V N^2} \right)^{1/3}$$

where U is the steady and uniform horizontal velocity, N is the buoyancy frequency defined above, Cp is the constant-pressure specific heat for air, and T_a are ρ_a are the ambient, ground-level temperature and density. This length must be interpreted as an estimate of the order of magnitude of the height above the fire to which the centerline of the plume will rise for the specified values of the fire size Q_l (GW) the wind speed V and the buoyancy frequency N. Because this relationship is derived from the governing equations, it should apply to the WTC tower fires as well as to oil-spill fires.

From BANG-FIR part I the characteristic length L is computed as a function of Q for different values of N and V for the tower of WTC. These plots indicate the sensitivity of the value L to changes in atmospheric stability and the wind speed.

Program banging - part 2 used the thermal element model and was performed over a domain, which included the top portions of both towers and horizontal lengths in each direction equal to a few tower heights. With these computations, we attempted to bound the total quasi-steady convective heat release from the fires in each tower by comparison of the observed smoke plume trajectory with that determined by the simulations.

Based on FEMA, for most of the simulations reported here, a grid of 108 nodes in each direction (1.26 x 10^6 total cells) was used. Computations required about 15 CPU hours on a 1 GHZ standard personal computer to simulate 500 s real time for the FDS1 computations and about 30 s real time for the FDS2 computations. The domain for the FDS1 computations was taken to be 600 m in both horizontal directions by 800 m in the vertical directions evaluating a cell size of 5.6 m by 5.6 m by 7.4 m. The domain for the FDS2 simulations was approximately 84 m by 84 m by 70 m, giving a cell size of 0.78 m by 0.78 m by 0.65 m. It was noted from the calculations the steady slate plume height increased very quickly with down wind distance. Where the rate of magnitude became smaller, the plume height was slow with down wind distance.

CS 6 Fire Simulation in the Global Analysis

After the aircraft impact occurred, it is important to simulate fire in postulating interior and exterior damage of a WTC tower.

For both undamaged towers, we modelled a story as having a total height for the initial assessment of 3.66 m, with a floor/truss thickness/ceiling combination of 1.04 m. Only a portion of the height for the initial assessment of each tower was included in the simulations. The model started two stories below the damaged ones and ended ten stories above, because buoyancy N causes the smoke and hot gas to rise. For the north tower, the model began at the 92nd story and included the 108th story. The south tower began at the 76th story and ended at the 93rd story. The outside wails of the undamaged stories of each tower were impenetrable, whereas the core was assumed to be open at both the top and bottom allowing gases to flow freely in and out. These were taken from the FEMA Report. A reference is made to the following data from FEMA Report.

The core modelled by two vertical shafts each extending 42 the core, one having a width of 2.5 m and the other a width of 14.6 m with a 7.4 m aisle separating the two. The larger shaft was taken to be hollow, with a slit of 3.2 m running vertically up the centre of both long faces of the shaft. These slits were constructed to represent openings shown by connecting floors vertically through the core, and can be regarded as a combination of designed vertical connections and damage produced connections. ne core shaft was open at both the bottom and the top of the model. The slit size in the core shall changes the interior ventilation for the model, and this interior ventilation should be varied systematically to determine its importance to the spread of smoke, hot gases and the fare. Only two cases were simulated, one with no slits in the core and the other with the 3.2 m slits as described above.

Damage and the fuel distribution on the inside of the tower must be postulated. As an attempt to bracket the interior damage, two very different damage scenarios were considered for a segment of the north tower. For the first scenario, it was assumed that five floors were damaged and collapsed into a pile of combustible rubble from the force of initial impact, the north face, to the core. Therefore, the damage geometry was effectively one large open space with the rubble treated as a big rectangular block on the floor. We assumed that the internal combustible material was spread uniformly over all of the interior surfaces in the damaged area including the block, and all surfaces burned at the same rate.

In a second case, it was postulated that the plane penetrated to the core of the north tower and that the floors remained standing up to the damage hole produced by the plane. In this case, most of the floor area, except for the plane hole remained as it was before the collision, and the fire burned over these long, narrow floors.

The design load for one floor of such a building is usually taken to be 460 kg/m^2 with as 90 kg/m^2 due to partitions and 370 kg/m^2 regarded as movable. Of this movable load, the combustible portion is generally taken to be 14 to 18.5 kg/m^2, but possibly ranging up to 140 kg/m^2, with an average load of 46 kg/m^2 still being reasonable way to look at these fires is to consider burning jet fuel to be the igniter of the existing fuel within the building. It must also be noted that the fuel loads might vary considerably with spatial location in each building.

CS7. Conclusion and Future Recommendations

The comments examined what can be learned from the extreme events of 11 September 2001 for the future design of tall buildings and the appraisal of existing ones. The aim has been comprehensively examine the safety issues arising from such event and to direct and improve provisions for building infrastructure which can be sustain future malicious with reduced risk of loss of life.

A comprehensive study carried out, especially on WTC Towers gave an insight of the existing design and how it is related to the progressive collapse of the towers. Since no two buildings are identical, more case studies need to be examined using international collaboration amongst respective professionals are needed to optimise occupant safety in extreme events. The fallowing conclusions should be noted on the draft report.

(A) Analysis

1. A three-dimensional dynamics hybrid finite element analysis is required on tall buildings core and frames using the load-time functions of various known aircraft. In order to assist the designers we have prepared such load-time functions plotted for a number of known aircraft. This plot is given Plate No.3. The buildings are made up of materials can early be checked for the aircraft impact.
2. It is vital to analyse floors of steel, concrete and composite for damage scenarios presented by aircraft hot fluid interacting with these floor. The report is devoid by such recommendations.
3. From the hot oil structural interaction, after the building was subjected to heavy impact from the aircraft, debris can result, they in turn produce impulsive loads and cause an impact to the exterior of the columns/walls and core. It is essential to have a through investigation of the debris impact which causes holes and air ventilation, as such would generate instant fire. BANG-FIRE Program can take such a case of instant fire. The structural integrity is vital.
4. Passive and Active fire protection shall form the basis of analysis. The passive fire could not be simulated due to shortage of time and must be pursued in using specific analytical approach
5. During this analytical analysis at no stage thermal expansion is created any problem. Under such instant load, 2 to 3% of load caused by thermal expansion is in our view, insignificant.
6. Due to aircraft impact, prior to the hot-fuel interaction the joints, according to analysis, where heavily loosened and are failed and fire together with hot fuel interaction presented a desired scenario.
7. The three dimensional dynamic instability (elastoplastic) analyses has produced using FEMVIEW and PATRON, dejected structures elements. The maximum dejection of a column element 10 m at ground level. This analysis is important for dejection with debris dust is still in progress and the international community must show an interest in producing 3D model of Debris-Dust-Dejection of structural elements. RROGRAM IMP interacting with DDD program have produced extremely clear scenario.

(B) DESIGN

On the de sign and safety side, it is an excellent draft and raised there in same important issues. Looking at the various recommendations we have reasons to believe that the fallowing needs urgent attentions;

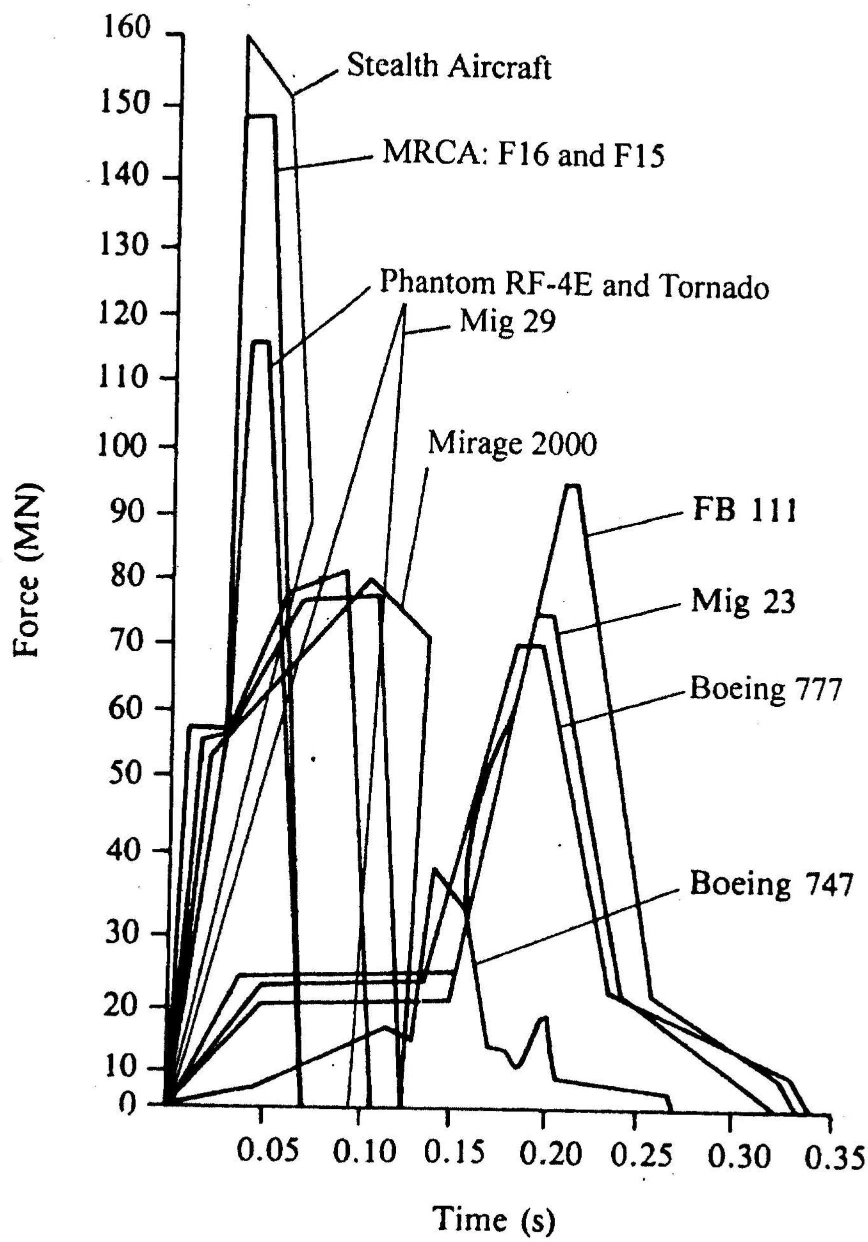
1. <u>Safety Cladding</u>: Our analysis indicates that use of laminated or toughened glass with fixing shall be designed to take into account of the potential explosion loading. Wherever is possible SIFCON Layers are employed which have improved load-deflection characteristics and stress-strain properties in comparison with normal concrete. The SIFCON panel between laminated

glasses subjected to blast loading provides 35% additional safety factor cladding and glazing of such a system cause less human injuries.

2. A comprehensive test program is need to design in solutions against with and without fire.
3. Security and Safety of Building Services : Design procedures supported by comprehensive and experimentation must produce robust and protected building services systems. The building must service complete "burn out" of contents.
4. Safety of Human Beings and Building Design: In order to reduce the probability of occurrence of extreme events, all designs must be carried out on time-load basis so as they have the potential to cause progressive collapse. Buildings above 25 storeys must be designed against impact and explosion with and without fire. Any height above 25 storeys buildings shall be provided with sky bridges, especially the buildings standing in parallel or any axis. The sky bridges above 25 storeys shall be on the basis of 4 No: floors/sky bridge. In order to make the building robust, the sky bridge would provide "stiff frame" effects and offer opportunities to stay longer in order to carry out substantial evacuation. Using crises cross positioned escalators in between sky bridges must provide potential escape routes. The physical size of these sky bridges shall not be less than those of staircase widths. Entrances to buildings must have separate air distribution zones with separate air supply and extract. The layout of the building shall be such that terrorists cannot find escape routes on grounds. This will be treated as part of strategies of deterrence needed for the protection vital installations.

   It is vital to ensure compartments in a building are gas tight and seals are sound on building completion, if new, by inspection, testing and cerfication.

PLATE 3



Time–impact function.

Appendix I

Extracts of Chapter 10

Explosion-Resistant Buildings
Design, Analysis, and Case Studies

2005, Approx 450p.
Hardcover , Eur149.25: £ 115.50
ISBN 3-450-20618-3

10.9. World Trade Centre (WTC 1 and WTC 2)

10.9.1. Data for three-dimensional finite element modelling

The following summarises the basic geometric data for WTC 1 and WTC 2:
(Note: the data is given for both towers. Where there is a difference, this has been identified).

- 1 Storey Height is generally 110 storeys plus 7 levels.
- 2 For WTC 1 roof height is 1368 ft (417 m) with 360′ or 110 m Television Tower
  For WTC 2 roof height is 1362 ft (415 m)
- 3 Square floor plate 207′-2″ (63.1 m): corners cham ford 6′-11″ (2.13 m) Long on each side
- 4 Floor space at each level 207′x 207′
- 5 Rectangular service core 87′ (26.5 m) x 137′ (41.75 m)
- 6 Bearing wall (exterior wall module) Ref: fig. 10.10

• 7	Welded columns Typical floor at each of the flat faces of the building	59 No columns 14″ (358 mm) square box section at 3′-4″ (1.06 m) closed spaces REF Fig. 10.15
• 8	Adjacent perimeter column interconnected at each floor level	52″ (1.321 m) deep spandrel plates
• 9	Plate thickness	Exterior walls = 1/4″ (6.3 mm) Base of the column = 4″ (100 mm)
• 10	Floor construction	(a) 100 mm light weigh concrete with 38 mm – 22 gauge non-composite steel deck open web joist floor system (b) Floor trusses In pairs with spacing 6′-8′ (2.03 m), Spanning 60′ (18.276 m) and 35.0′ (10.67 m) at the ends of each core

The following summarises carefully by studying literature and drawings of WTC 1 and WTC 2 the loads and material properties associated with these two towers:

• 1	Floor imposed load Building corner load	100 lb/ft^2 (4.788 KN/m^2) 55 lb/ft^2 3.79 KN/m^2)

10.9. World Trade Centre (WTC 1 and WTC 2)

10.9.1. Data for three-dimensional finite element modelling

The following summarises the basic geometric data for WTC 1 and WTC 2:
(Note: the data is given for both towers. Where there is a difference, this has been identified).

- 1 Storey Height is generally 110 storeys plus 7 levels.
- 2 For WTC 1 roof height is 1368 ft (417 m) with 360′ or 110 m Television Tower
  For WTC 2 roof height is 1362 ft (415 m)
- 3 Square floor plate 207′-2″ (63.1 m): corners cham ford 6′-11″ (2.13 m) Long on each side
- 4 Floor space at each level 207′x 207′
- 5 Rectangular service core 87′ (26.5 m) x 137′ (41.75 m)
- 6 Bearing wall (exterior wall module) Ref: fig. 10.10

• 7	Welded columns Typical floor at each of the flat faces of the building	59 No columns 14″ (358 mm) square box section at 3′-4″ (1.06 m) closed spaces REF Fig. 10.15
• 8	Adjacent perimeter column interconnected at each floor level	52″ (1.321 m) deep spandrel plates
• 9	Plate thickness	Exterior walls = 1/4″ (6.3 mm) Base of the column = 4″ (100 mm)
• 10	Floor construction	(a) 100 mm light weigh concrete with 38 mm – 22 gauge non-composite steel deck open web joist floor system (b) Floor trusses In pairs with spacing 6′-8′ (2.03 m), Spanning 60′ (18.276 m) and 35.0′ (10.67 m) at the ends of each core

The following summarises carefully by studying literature and drawings of WTC 1 and WTC 2 the loads and material properties associated with these two towers:

• 1	Floor imposed load Building corner load	100 lb/ft^2 (4.788 KN/m^2) 55 lb/ft^2 3.79 KN/m^2)

Section 10.3

• 2	Boeing 767 – 200ER Commercial Aircraft (a) Maximum rated take off load/weight	3.95×10^3 lbf (376672 kg)
• 3	Basic dimensions of the aircraft 767-200 ER	159′ (48.45 m) length x 156′ (47.85 m) wide x 53′ (16.155) high from ground
• 4	Rated cruise speed	530 miles/hr Actual for WTC 1 470 miles/hr Actual for WTC 2 590 miles/hr
• 5	Tower Impacted floors	WTC 1 – Between floors 94 and 98 WTC 2 – Between floors 78 and 84
• 6	Impact Duration as reported (approx)	WTC 1 → 10 seconds Average WTC 2 → 8-10 seconds Average
• 7	Area Impacted	30 m^2 for WTC 1 35 m^2 for WTC 2

SEA LOAD-TIME FUNCTION FOR AN AIRCRAFT IN APPENDIX I

• 8	Collapsed after impact	WTC 1→After 102 minutes in 5 seconds WTC 2→After 56 minutes in 10 seconds
• 9	Approx. sealing gas temperature	1000 °C – 1100 °C
• 10	Approx. dead load	88 lb/ft^2 (4.213 KN/m^2)
• 11	Floor beams	Exterior: W24x61 Interior: W18x50
• 12	Steel plate thickness through out in bolded joints	3/8″ (9.5 mm) thick 12″ (305 m) x 6 ½″ (65 mm) PL
• 12	Bolts (as evident from drawings)	¾″ (19 mm) spaced along rows 3 ½″ (90mm)
• 13	Weld material	Nominal yield strength = 50 Ksi (342 MN/m^2)
• 14	Steel Grades 12ND	42 Ksi (289.6 MN/m^2) to 100 Ksi (684.5 MN/m^2)
• 15	Metal Deck spanning (a) Parallel to the main trusses	13′-4″ (4.064 m)

	supported by transverse bridging trusses	
	(b) Intermediate deck, support angles, spacing from transverse trusses	6'-8" (2.03 m)
	(c) Core concrete fill on metal deck supported by floor framing of rolled sections, in turn, supported combined wide shaped flanges and columns of box sections	14" (350 mm) x 36" (915 mm) deep
• 15	Outrigger truss system for stiffening of frames	103 floor – 110 floor
• 16	Structural tube framing base of the exterior wall frame	3ND columns 14" (358 mm) box each joint to form base columns
• 17	Cantilever transfer girder detail	46' (14 m) span, 2 to column continuous down. At continuous down = 4'-6" (1.37 m) 9 ft (2.74 m) depth near ranger with spacing 6'-9" (2.057 m)

Note: For other material properties reference is made to Tables (10.1) to (10.8). In the finite element analyses where stresses, strains for each element reached. The limit values, the element has yielded. This is discussed later on in this section.

Table (10.1) Heat Release Rate for Office Module

Heat Release (KW)		Time (seconds)
0		0-1200
1000		420↑
2000	Slow - Rate	↑450-600
4000		↑480-660↓
6000		0550↑↓
7000		600

Section 10.5

Table (10.2) Temperature – Time ASTM E119

Temperature °C	Time Minutes
25	1.5
200	2.0
400	4.0
600	7.5
800	20
1000	60

Table (10.3) Stress-strain curve structured steel ASTM A36 steel at 600°C (1112 F°)

Stress N/mm^2 σ	Strain ε in/in
0	0
100	0.08
130	0.02
150	0.12

Table (10.4) Critical Temperature for various types of steel

Steel	Temperature
Columns	538 °C
Beams	593 °C
Open-web steel joists	593 °C
Reinforcement	593 °C
Pre-stress steel	426 °C

Table (10.5) Strength – Reduction factor Fyt/Fy at Elevated Temperature °C

Fyt/Fy	Temperature °C
1	0
0.9	200
0.8	300
0.7	400
0.4	600
0.2	700

Section 10.6

Table (10.6) Young's modulus at Elevated Temperature °C Reduction values

E/E_0	Temperature °C
1	0
0.97	50
0.95	100
0.85	300
0.82	400
0.63	500
0.20	600

Table (10.7) Box columns 14" x 14" Temperature versus time based on E119

Temperature °C	Time (minutes)
100	5.0
200	7.5
300	10.0
400	12.5
600	15.0
700	20.0

Table (10.8) Warping and Buckling

Warping Wvc_b	M_1/M_2
1.0	-1.0
1.25	-0.5
2.25	+0.5
2.75	+1.0

10.10. Finite Element Modelling of WTC-1 or WTC-2

10.10.1. Introduction

In order to make more efficient use of the inelastic response of the building system and its damage scenario, the relevant numerical analysis and analytical work should be based on keeping in mind where the damaged areas were visible and where columns and floors statistical data in the FEMA Report have shown as disaster areas. This will be quite useful to check also the analytical results. Where the classification of the damage scenario is not clear, the normal course of finite element analysis shall be carried out. This section is entirely based on the WTC1 and WTC2 building collapse analysis. For the dynamic finite element analysis, a reference is made to Appendix I where derivations of various cases have been studied and analytical formulations are recorded.

Finite Element Analysis of WTC1 and WTC2: Basic Philosophy
Plate No 10.2 shows a typical 3D finite element mesh scheme, comprising of 3D line elements and series of these elements are connected by nodal points through out in the WTC1 framed building. The concrete floors have 4-Noded is o parametric elements and their nodes are linked with 2 noded truss rods of the trusses. The same scheme is continuous for the supporting trusses in transverse directions.

Both towers and their cores are modelled explicitly. The steel connections such as moment and shear connections are spandrel – column connections in all major framing are also explicitly modelled. In the intermediate framing, beams are in corporated as grids.

Typical mess schemes are given in figures (10.09) to (10.12) for individual local F.E. analysis for buckling, warping and interactive analyses when members are under loads caused by either impact – cum – blasts.

Basic formulations for the steel deck slab system are complex. In this analysis the system was modelled at each floor level as composite with clear material properties. T he elements refined systematically to obtain key out put data, specifically in the regions of heavy damage where F.E. mesh schemes were refined. PROGRAM BANG-BLAST has been used to carry out damage analysis using different models.

(a) Impact from 767-200 ER.
(b) Assessment of loose joints buckling and plasticity zones.
(c) Blast load defined for WTC1 and WTC2.
(d) (b) + (c) algebraically added results: check for any damage scenario defined by members crushing, yielding and cracking with and without buckling / warping.
(e) (b) + (c) + fire ball loads. The fire ball investigation includes fuel – structural interaction. BANG-FIR is called upon in the main program. The out put is algebraically added to (a) + (b). Check by FLAG, whether or not damage scenario has further intensified or spread to other elements.

The jet fuel has been distributed over multiple floors, and some have been transported to other locations. Some have assumed been absorbed by carpeting or other furnishings, consumed in the flash fire in the aerosol, expelled and consumed externally in the fireballs, or flowed away from the fire floors. Accounting for these factors, it is believed that all of the jet fuel that remained on the impact floors was consumed in the first few minutes of the fire. The wind speed at heights equal to the upper stories of the towers was in the range of 10-20 mph. The outside temperatures over the height of the building were 20-21 °C (68-70 °F). These effects are considered in the loading cases.

The modelling suggests a peak total rate of fire energy output on the order of 3-5 trillion Btu/hr, around 1-1.5 gigawatts (GW), for each of the two towers. From one third to one half of this energy is assumed to flow out of the structures. This vented energy is the force that drove the external smoke plume. The vented energy and accompanying smoke from both towers combined into a single plume. The energy output from each of

Section 10.8

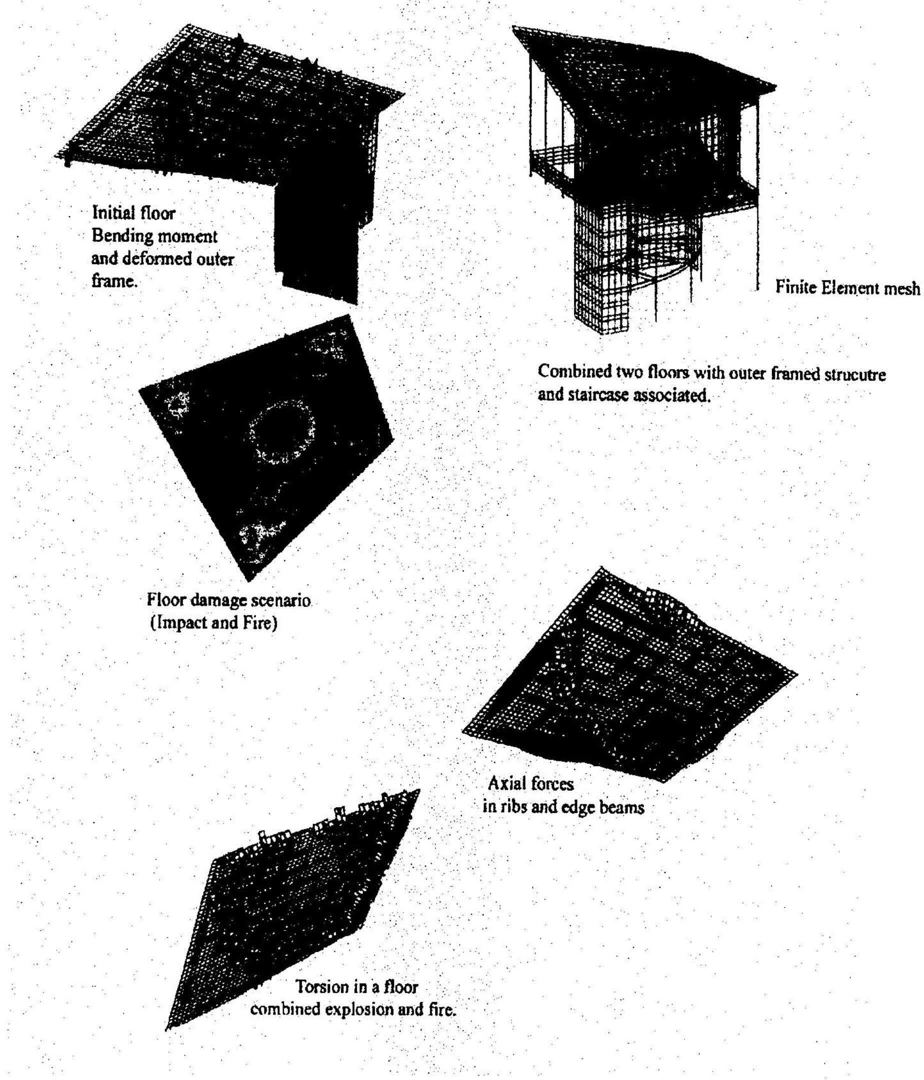
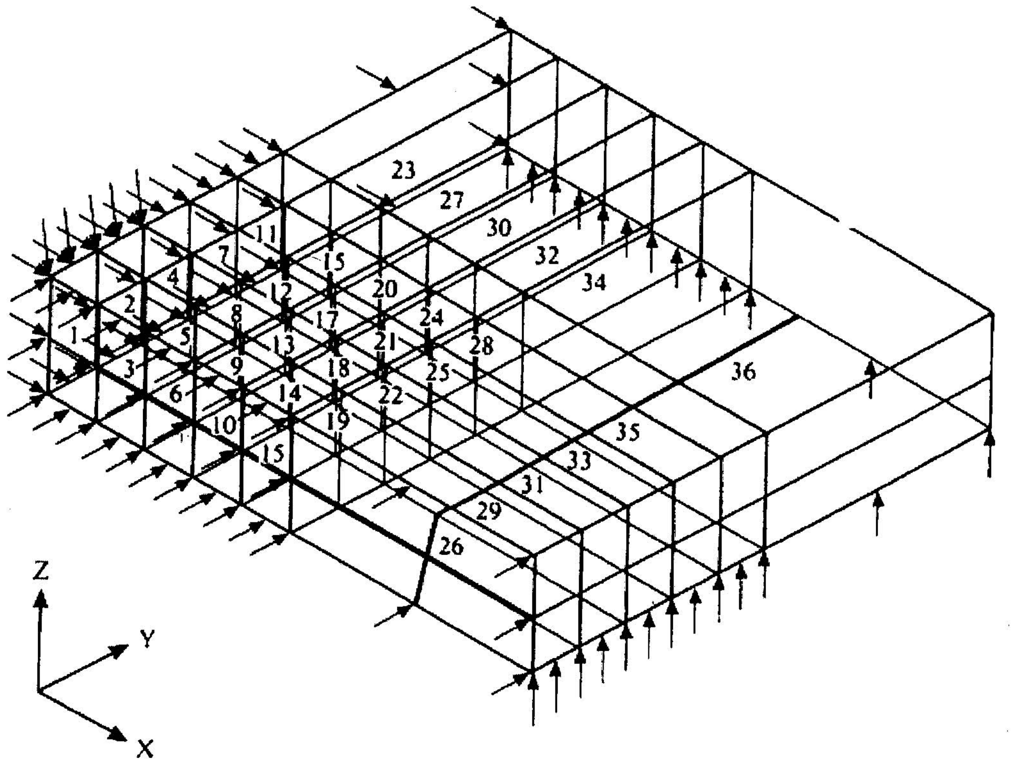


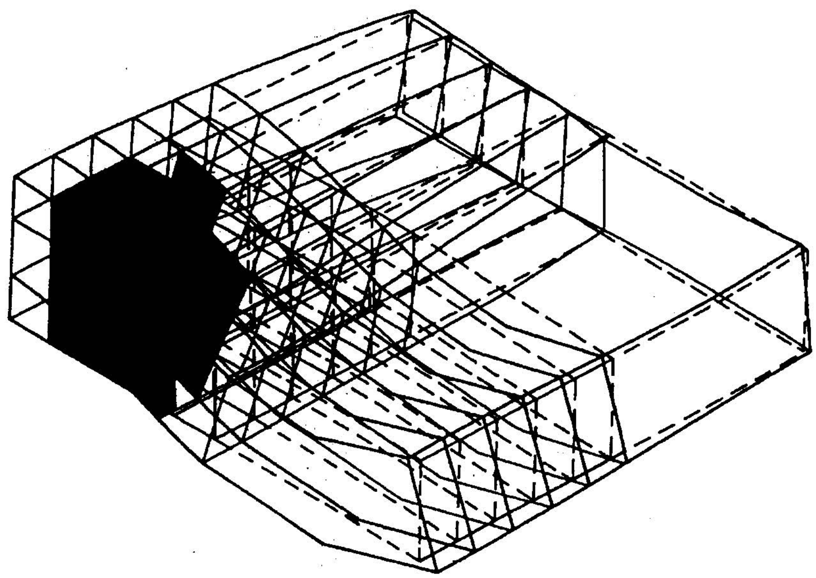
Fig.(10. 9) Typical floor-core deformations

PLATE 4

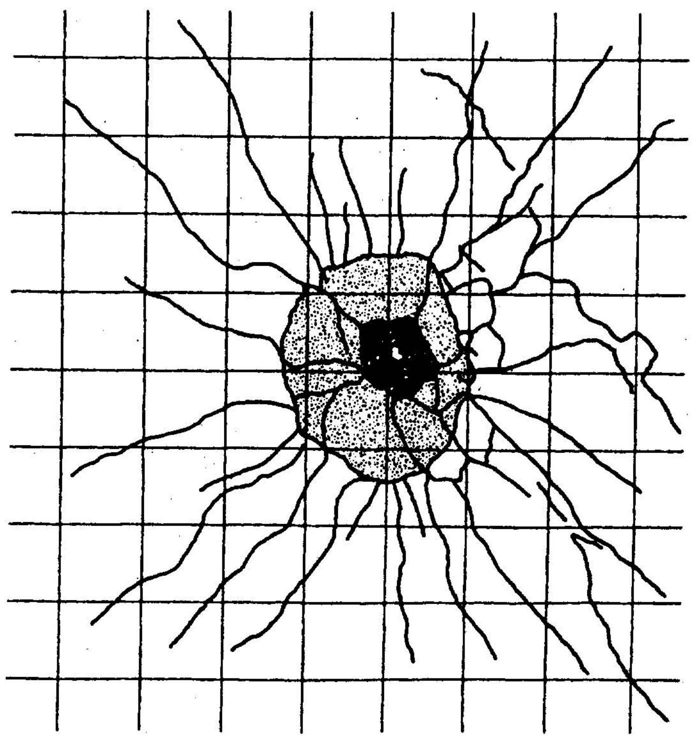


Model of one-quarter of the slab showing support condition load.

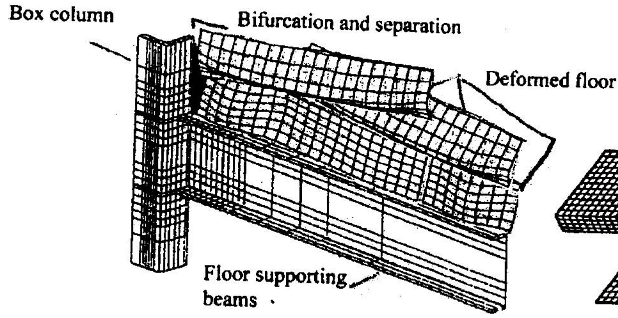
PLATE 5



pluggea-out zone in three dimensions.



Final element results for shear cone and cracking.



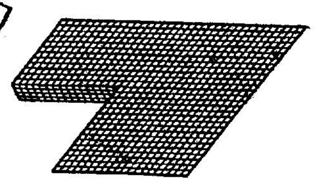


Fig.(10.10)(a) Floor on floor supporting beams with Box columns
-Finite Element Mesh scheme

Fig.(10.10)(b) Undeformed Deck
-Mesh Scheme 4 noded
Isoparametric Elements

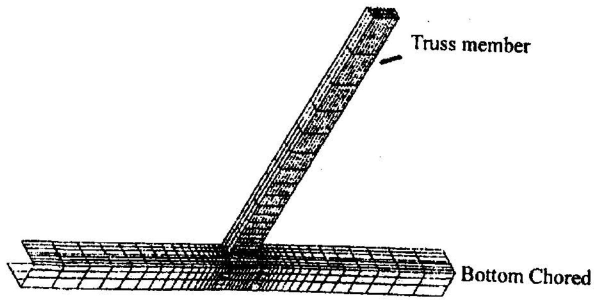


Fig.(10.11) Finite Elemet Mesh Scheme for trusses

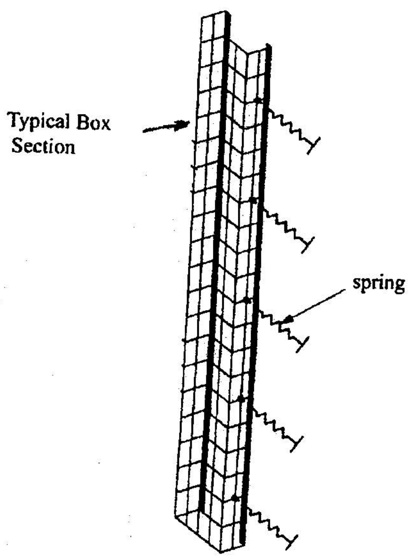


Fig.(10.12) Box section column interacting with floors

Section 10.12

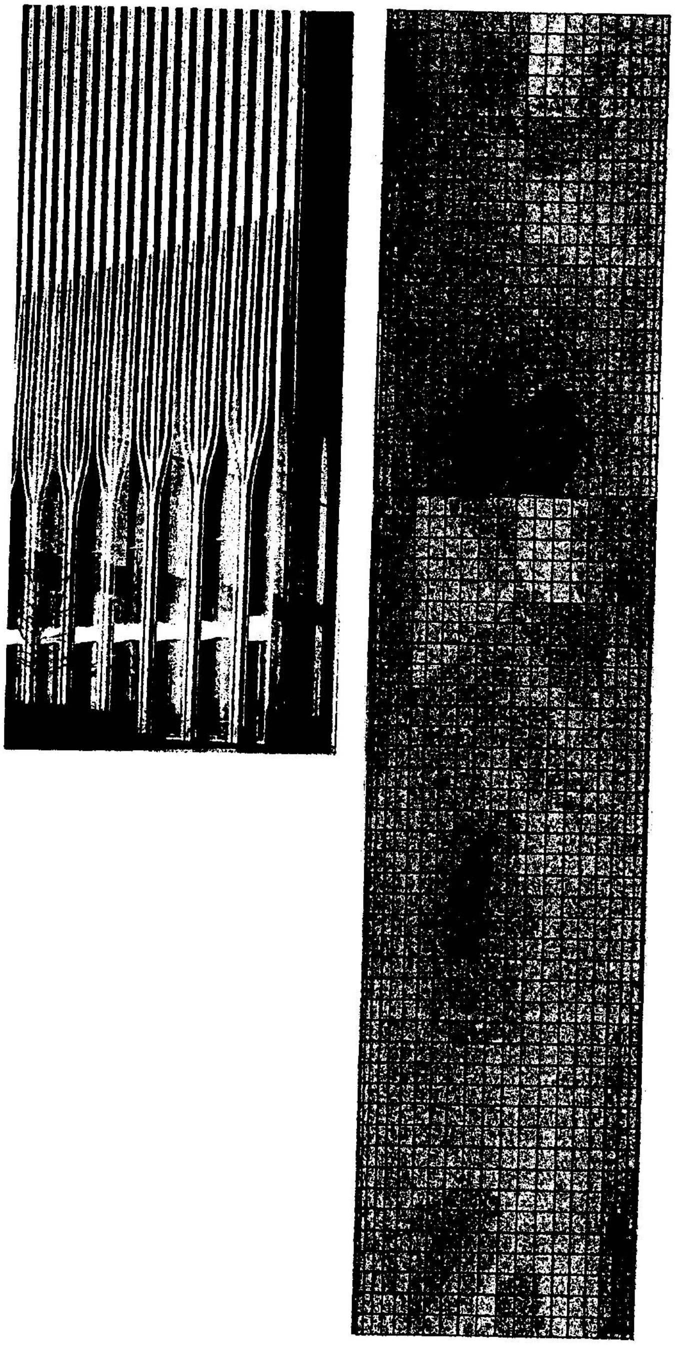


Fig.(10.13) A damage scenario of WTCI at and around Impact area the two buildings is similar to the power output of a commercial power generating station. The modelling also suggests ceiling gas temperatures of 1,000 °C (1,800 °F), with an estimated value of plus or minus 100 °C (200 °F) or about 900-1,100 °C (1,600-2,000 °F). A major portion of the uncertainty in these estimates is due to the scarcity of data regarding the initial conditions within the building and how the aircraft impact changed the geometry and fuel loading. Temperatures may have been as high as 900-1,100 °C (1,700-2,000 °F) in some areas and 400-800 °C (800-1,500 °F) in others.

The viability of a 3-5 trillion Btu/hr (1-1.15 GW) fire depends on the fuel and air supply. The surface area of office contents needed to support such a fire ranges from about 30,000-50,000 square feet (2787 m^2 – 4645 m^2) depending on the composition and final arrangement of the contents and the fuel loading present. Given the typical occupied area of a floor as approximately 30,000 square feet, it can be seen that simultaneous fire involvement of an area equal to 1-2 entire floors can produce such a fire. Fuel loads are typically described in terms of the equivalent weight of wood. Fuel loads in office-type occupancies typically range from about 4-12 psf (0.191/0.0515 kN/m^2) with the mean slightly less than 8 psf (0.382 KN/m^2). File rooms, libraries, and similar concentrations of paper.

Based on photographic evidence, the fire burned as a distributed collection of large but separate fires with significant temperature variations from space to space, depending on the type and arrangement of combustible material present and the available air for combustion in each particular space. Consequently, the temperature and related incident heat flux to the structural elements varied with both time and location. This information is not currently available, but has been modelled with advanced CFD fire models.

Damage caused by the aircraft impacts is believed to have disrupted the sprinkler and fire standpipe systems, preventing effective operation of either the manual or automatic suppression systems. Even if these systems had not been compromised by the impacts, they would likely have been ineffective. It is believed that the initial flash fires of jet fuel would have opened so many sprinkler heads that the systems would have quickly depressurised and been unable to effectively deliver water to the large area of fire involvement. Further, the initial spread of fires was so extensive as to make occupant use of small hose streams ineffective.

It is assumed that the structural joints, at the level of impact, are 95% in effective is the joints have failed. Areas outside impact zone, the strength reduction factor is, for the purpose of analysis, is 50% assumed to be 50%.

As stated earlier the impact of the aircraft into WTC 1 substantially degraded the strength of structure to withstand additional leading and also made the building more susceptible to fire-induced failure. Among the most significant factors:

1. The force of the impact and the resulting debris field and fireballs probably compromised spray-applied fire protection of some steel members in the immediate area of impact. The exact extent of this damage will probably never be known, but this likely resulted in greater susceptibility of the structure of fire-related failure.

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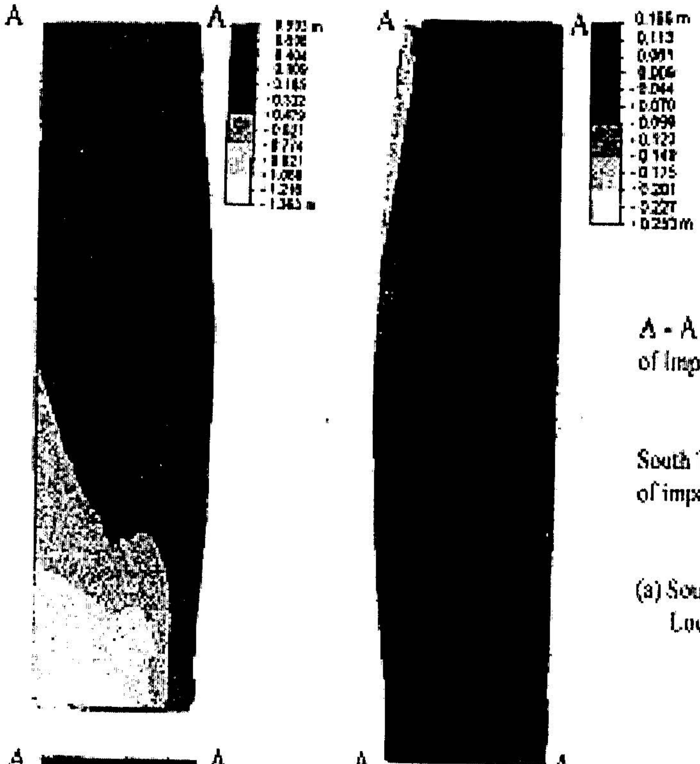
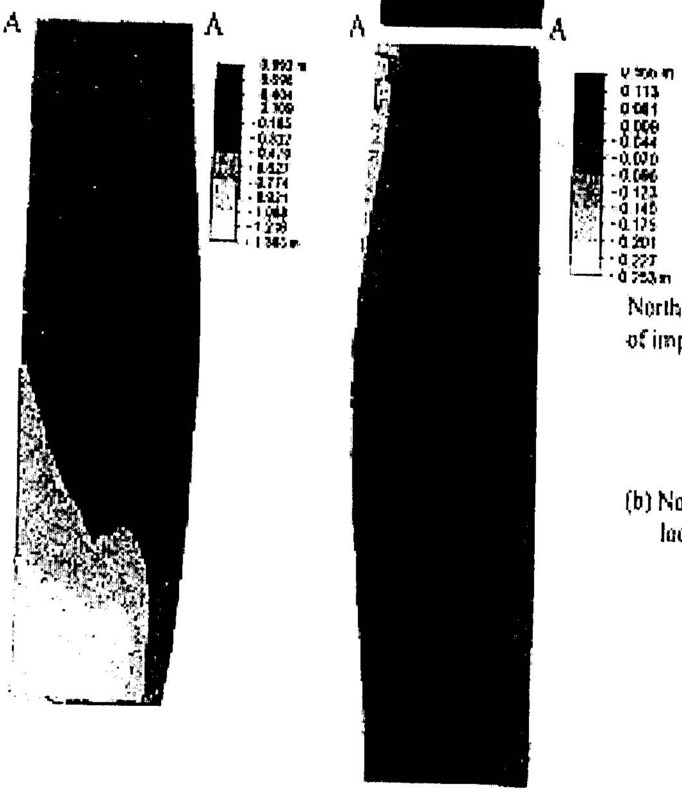


A - A Top Boundary level of Impact

South Tower from the level of impact.

(a) South Tower damaged zone Localised area.



North Tower from the level of impact.

(b) North Tower damage zone localised areas.

Section 10.15

2. Some of the columns were under elevated states of stress following the impact, due to the transfer of load from the destroyed and damaged elements.

3. Some portions of floor framing directly beneath the partially collapsed areas were carrying substantial additional weight from the resulting debris and, in some cases, were likely carrying greater loads than they were designed to resist.
As fire spread and raised the temperature of structural members, the structure was further, stressed and weakened, until it eventually was unable to support its immense weight. Although the specific chain of events that led to the eventual collapse will probably never be identified, the following effects of fire on structures may each have contributed to the collapse in some way discussion of the structural effects of fire.

4. As floor framing and supported slabs above and in a fire area are heated, they expand. As a structure expands, it can develop additional, potentially large, stresses in some elements. If the resulting stress state exceeds the capacity of some members or their connections, this can initiate a series of failures.

5. As the temperature of floor slabs and support, framing increases, these elements can lose rigidity and sag into catenary action. As catenary action progresses, horizontal framing, elements and floor slabs become tensile elements, which can cause failure of end connections and allow supported floors to collapse onto the floors below. The presence of large amounts of debris on some floors of WTC 1 would have made them even more susceptible to this behaviour. In addition to overloading the floors below, and potentially resulting in a pancake-type collapse of successive floors, local floor collapse would also immediately increase the laterally unsupported length of columns, permitting buckling to begin. As indicated in Appendix B, the propensity of exterior columns to buckle would have been governed by the relatively weak bolted column splices between the vertically stacked prefabricated exterior wall units. This effect would be even more likely to occur in a fire that involves several adjacent floor levels simultaneously, because the columns could effectively lose lateral support over several stories.

These factors 1 to 5 taken from the FEMA report are in line with the analysis presented in the text.

Progression of Collapse
As in WTC 1, a very large quantity of potential energy was stored in the building, during its construction. Once collapse initiated, much of this energy was rapidly released and converted into kinetic energy, in the form of the rapidly accelerating mass of the structure above the aircraft impact zone. The impact of this rapidly moving mass on the lower structure caused a wide range of structural failures in the floors directly at and below the aircraft impact zone, in turn causing failure of these floors. As additional floor plates failed, the mass associated with each of these floors joined that of the tower above the impact area, increasing the destructive energy on the floors immediately below. This initiated a chain of progressive failures that resulted in the total collapse of the building.

A review of aerial photographs of the site, following the collapse, as well as identification of pieces of structural steel from WTC 2, strongly suggests that while the top portion of the tower fell to the south and east, striking Liberty Street and the Bankers Trust building, the lower portion of the tower fell to the north and west, striking the Marriott Motel (WTC 3). Again, the debris pattern spread laterally as far as approximately 400-500 feet from the base of the structure. These effects are not considered in two towers.

Construction of WTC 1 resulted in the storage of more than $4x10^{11}$ joules of potential energy over the 1,368-foot (417 m) height of the structure. Of this, approximately $8x10^{9}$ joules of potential energy were stored in the upper part of the structure, above the impact floors, relative to the lowest point of impact. Once collapse initiated, much of this potential energy was rapidly converted into kinetic energy. As the large mass of the collapsing floors above accelerated and impacted on the floors below, it caused an immediate progressive series of floor failures, punching each in turn onto the floor below, accelerating as the sequence progressed. As the floors collapsed, tins left tall freestanding portions of the exterior wall and possibly central core columns. As the unsupported height of these freestanding exterior wall elements increased, they buckled at the bolted column splice connections, and also collapsed. Perimeter walls of the building seen, to have peeled off and fallen directly away from the building face, while portions of the core fell in a somewhat random manner. The perimeter walls broke apart at the bolted connections, allowing individual prefabricated units that formed the wall or, in some cases, large assemblies of these units to fall to the street and onto neighbouring buildings below.

10.10.2. WTC 2

10.10.2.1. Initial Damage From Aircraft Impact

United Airlines Flight 175 struck the south face of WTC 2 approximately between the 78th and 84th floors. The zone impact extended from near the southeast corner of the building across much of the building face (Figures 2-4 and 2-5). The aircraft caused massive damage to the south face of the building in the zone of impact (Figures 2-6 and 2-7). At the central zone of impact corresponding to the airplane fuselage and engines, six of the prefabricated, three-column sections that formed the exterior walls were broken loose from the structure, with some of the elements apparently pushed inside the building envelope. Locally, as was the case in WTC 1, floors supported by these exterior wall sections appear to have partially collapsed. Away from this central zone, in the areas impacted by the outer wing structures, the exterior steel columns were fractured by impact. Evidence shows from 27 to 32 columns over a 5-storey range were destroyed along the south building face. Partial collapse of floors occurred over a horizontal length of approx. 70 ft (214 m) while floors in the other portions were intact. A landing gear from the aircraft crashed through the roof of WTC 2. The roof was located six blocks to the North. A portion of the fuselage was lying on the roof of WTC 5. There was a lot of debris in WTC 2 as well. This effect is not taken in the analysis.

The same types of structural behaviours and failure mechanisms previously discussed are equally likely to have occurred in WTC 2, resulting in the initiation of progressive collapse, approximately 58 minutes (3360 seconds) after the aircraft impact. Review of footage of the WTC 2 collapse suggests that it probably initiated with a partial collapse of the floor in the southeast comer of the building at approximately the 80th level. This appears to have been followed rapidly by collapse of the entire floor level along the east side as evidenced by a line of dust blowing out of the sidle of the building.

As this floor collapse occurred, columns along the east face of the building appear to buckle in the region of the collapsed floor, beginning at the south side and progressing to the north, causing the top of the building to rotate toward the east and south and to begin to collapse downward. It should be noted that failure of core columns in the southeast corner of the building could have preceded and triggered these events

10.10.3. Analysis of Results from the global Analysis

The full simulation of he aircraft 767-200ER with a fuel-filled wings impacting WTC-1 Tower has been carried out. The key components were meshed out together with exterial walls columns wall panels and composite floors. The aircraft engine has a fine mesh of hybrid elements. At the impacting level both mesh schemes are provided with contact / gap elements For the purpose of interactive analysis Hallquist et al method of master slave and nodes have been adopted. The slave modes are constrained to slide on master segments after impact occurs and must remain on the master segment until tensile interface force develops. A zone in which a slave segment exists is known as SLAVE ZONE. A void exists between slave and master line. At impact level whether it is due to the aircraft or debris, it is necessary to update the location of each slave node by finding its closet master node or the one on which it lies. In the collapse analysis it becomes necessary that for each master segment one must find out the first slave zone that overlaps. Generate finally the existence of the tensile interface force. Constraints are imposed on global equations by the transformation of the nodal displacement components of the slave nodes among the contact interface. The slave nodes will have no normal degrees of freedom and the normal force components are distributed near by master nodes using explicit time integration in the finite element solution procedures.

There after the impact and release conditions are imposed. This method in the finite elements analysis identifies the contact point that can become trivial during the execution of the analyses. The impact of the aircraft developed a hole of not less than ≤ 30 m^2 by breaking the exterior columns and the floor slabs. The analysis shows, the area filled with hot fuel (800 – 1000 °C) completely developed failure zones and some cases rupture columns and floors. The debris formed impacted the walls and created large spaces for ventilation, allowing 70 seconds to produce flume and fire, initially in the impacted areas. The fuel structure interaction analysis showed continuous damaging and enlarging deformations, particularly to the floors with exterior columns bowed inward. The impact analysis further showed that the aircraft wing segments were fragmented ($f_y > 550$ MN/m^2) and penetrated. Columns and floor zones filled with spraying hot fuel moving down from floor to floor. The hot fuel-cum-debris was sufficient to create a surge of rapidly filling the floors (93rd-97th floors). Debris integrate at this level to dust ridden plume. The ventilation created in the wall (east and south side of the tower) due to debris impacted as well created plume and ignited mist out the entrance gash and blown out window elements. The fire ball resulted. The finite elements analysis, using 3D FEMVIEW and PATRON, indicated continuous debris filled smoke for around 6000 second after which the entire structure collapsed. When the instability analysis performed, the exterior columns showed more "bowing in" at least 25% more than the combined load conditions. Where the exterior columns are not affected (outside impacted zone), they displayed enough residual capacity. The impact analysis re-evaluated the results and vertical approach angle below horizontal 13.6 °C (heading down ward) for WTC 1 Tower while maintaining 180° lateral approach angle and the vertical approach by 8° (heading downward for WTC 2 Tower. In both cases the average roll angle taken to be 32 °. The total time for load-time function diagram was 0.6

seconds for both towers. The progressive analysis of collapse involved different timings for the WTC-1 and WTC-2. The same aspect time, Δt = 200 seconds plus, was considered. Not having enough information on the damage to the thermal insulation, it was assumed that aircraft and debris impact have damaged and dislodged the insulation due to inertia forced developed as a result.

BANG-FIRE results when algebraically added to those obtained from aircraft and debris impactive forces indicated that the floors influenced initially by such forces, the hot jet fuel interaction with steel and steel-concrete composites have damaged zones more than the temperature expansion phenomenon which was around 2 to 3 %. The fuel temperature could not be less than 900°C for one hour at least, thus bringing the steelwork taking not more than 600°C would have contributed to the melting of the structural elements, the zones above the impact zone would be solid and undamaged, thus bring about the vertical collapse scenario. Since the ventilation created would have injected oxygen, thus causing fire which also created high temperatures to cause certain zones of WTC-1 and WTC-2 building structures the initiation of collapse. The temperature modelling alone without impact took almost twice the time of the collapse of WTC-1. Under combined impact fuel and fire loads generated the total collapse of WTC 2 in the specified time. This indicates that aircraft impact had substantially weakened the tower structures and joints welds etc. The impacts have caused greater instability without creating total collapse. The sagging of the floors had increased. Although the floors on the north side of the tower had sagged first, when the fuel plus fires moved toward south. Now the south side floors had sagged to the point where the south perimeter columns bowed inward. The finite element analysis showed that the south exterior wall had bowed inward by 1350 mm.

The robustness of the towers with that truss in particular was designed for normal loads with wind and earthquake effects. After seeing the tower WTC-1 with the core the floors and perimeter walls weakened major instability exhibited in the south wall. The hat truss could not be transferred the loads thereby causing the columns collapsed and the load via spandrels could not have been transferred. The upper section as predicted by the finite element like a high section started tilting and the upper section collapsed on to the floor in WTC-1. Top sway around 675 mm to the north. For maximum displacement value of the tower was achieved using hybrid finite element at 2.5 seconds. The impact position of UA Flight 175 was 7 m from the east corner of WTC-2. This is the off-centre called oblique impact produced torsion in the upper part and caused counter clock movement. The floors considered under direct impact were 77 to 85. The bulk of impact damage was according the finite element analysis was confirmed to six floor. The aircraft wing laden with fuel struck the tower WTC-2.

The heavier damage was discovered in 79th floor due to sheltering of aircraft engine and wings, especially damaged the floor slabs down to the building core. The fuselage when interacted with 80th and 81st floors, the damage scenario was worse. The impact showed the collapsed spandrels and cruised part of the 82nd floor slab with severed columns and the core. The photographs showed as within about one half of a second, dust and debris flew out of windows on the east and the north faces. Several small fireballs of atomized jet fuel burst from windows on the east face of the 81st and 82nd floors loading a large fireball that spanned the entire face. Almost simultaneously, three fireballs came from the east side of the north face. The largest came from the 80th through 82nd floors. A second, somewhat smaller one came from the 79th floor.

The finite element analysis showed only the same fuel-structure-interaction. The results were quite similar to WTC-1 except the physical conditions of the tower determined with inward bowing of columns. The tower lost in half the time the ability to support upper solid floors. The progressive analysis showed that the top of the tower continual tilted to the east and south. Using the aspect time Δt = 200 s, the tower began to collapse at earlier time when compared with the WTC-1 tower. Due to oblique impact the impact damage was more severe to the WTC-2 core. The causes can be due jet fuel spray into the interior of the building causing rapid fire, sagging of the east floors, pulling forces to the east perimeter columns with reduced load carrying capacity and heavily weakened and unprotected steel yielded and plastic hinges developed at various positions.

10.10.4. A Comparative Study of WTC-1 Tower Results

An independent assessment of the validity of tower step-by-step collapse scenarios is tabulated using both observed and computed od simulated phenomena. The insulation ate assumed ineffective in floors covering impact zones.

WTC- 1 Tower		
	Observation	**BANG-F Results**
1	The aircraft impact did occur at the tower and the tower did not collapse and with stood the impact at the initial time.	The computer simulation after impact showed no sign of major collapse. At increments, the tower still stood and resisted design loads on exterior column. In 20th incremental process, the results showed around 8% reduced margin.
2	The south wall bowed at 10.23 am inward along the entire south face of 94th floor to 100th floor. The maximum bowing based on FEMA Report was 55" on the 97th floor.	The instability part of the analysis indicated that buckling occurred at the level of 97th floor around 1.375 m along with the tilt angle of around 10° in the direction of south. The total time registered to be 60,000 seconds.
3	At the structural collapse due to impact and fire, the top building section above impact zone tilted enormously in the south and no discernable east and west component in the tilt.	The analysis showed that thermal expansion was resisted by that truss. Core to the external walls, exterior columns splices and spandrel completely failed the hot fuel structural composite slab interaction initiated the collapse of six floors. Debris impact created ventilation holes and fire analysis took over from fuel analysis, thus created maximum load on core and external walls which exceeded when the process reached at 750°C where this intervened and make the components declared failed and (major parts) when $T_\theta = 600°C$, the solid part of the building above impact zone tilted and the bottom structure acted as like "magma" thus creating opportunity for nearly vertical collapse.
4	As clouds and dust obscured. The view the building section began to fall down nearly vertically. At 102 minutes from the impact of the air craft, the collapse initiated	The global instability segment within Program BANG-F, supported by program F-PATRAN to register viewing instantly, reached the limit over 1. South side bowed significantly. The program stopped at 6200 seconds from the time of impact. All elements collapsed. Flickering occurred at that level in F-PATRA indicating the program collapsed and non-functional and finally stopped.

Section 10.20

10.10.5 A Comparative Study of WTC-2 Tower Results

A similar approach was adopted for WTC-1 towers. The tower remained upright –with significant reserve capacity after aircraft impact and the initiation of hot-fuel structural interaction. The east perimeter wall, as indicated by BANG-F showed inward bowing of around 250 mm at floor 80. The bowing was extended and instability to 78th to 83rd floors. When BANG-F called upon the instability and F-PATRON, the results showed a greater tilt +8° to the east prior to the significant downward movement of the building section above the level of impact. Around θ = 30° tilt was registered by the instability analysis. The time of collapse initiation registered by program BANG-F together with sub programs duly intervened for component failure at different times was 2880 seconds.

10.10.5.1 Practical Solution to Twin Towers

The geometry of the twin tower is assumed to alter. Sky bridges of intervals of 4 floors were introduced between WTC-1 and WTC-2. A total number of 25 sky bridges were adopted. A rigid frame concept was introduced. The aircraft impact plus fire plus hot fuel loads apart from usual design loads were considered. Various impact angles on south and north sides were considered for the aircraft impact while keeping the roll angle to be 32°. The collapse of one tower took 5 hours and 25 second when aircraft was only considered. On combined loading the disaster scenario for one of the rigid towers reached 2 hours and 25 minutes. The analyses was repeated by introducing the rigidity of escalators or moving walks, placed inclined positions to pave the way for the quick removal of the population. The new factor of safety against impact alone was 15, against – collapse time of 15-2 = 13 hours when instability analysis intervened. In association with the blast loading effects, the margin of safety was reduced to 7 against 5 hours and 35 minutes and 30 seconds. Only one tower failure phenomenon was considered with the out come showed five sky bridges failed. When escalators and moving walkways were ignored, it is concluded that sky bridges need to be introduced at suitable levels.